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This report summarizes the major findings during the second year of a five-year research project with the ultimate goal of developing a light-weight, durable, strong and impact-resistant ceramic composite for use in advanced constructed facilities. During the first year of this project, short-fiber reinforced ceramic composites were identified to be the class of ceramic materials with the highest potential for development into a construction material. A model composite system was also chosen. In this project year, work has concentrated on the processing and preliminary testing of model composites as well as on the theoretical prediction of pre-peak behavior of short-fiber composites. Also, a study on the potential of ceramics construction as well as obstacles to its use were carried out to provide a foundation for future work.

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FIBER REINFORCED STRUCTURAL CERAMICS FOR CONSTRUCTION

Final Technical Report

by

Victor C. Li (Principal Investigator)
and Christopher K.Y. Leung

Period: January 1, 1988 - December 31, 1988

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Introduction

This report summarizes the major findings during the second year of a five-year research project with the ultimate goal of developing a light-weight, durable, strong and impact-resistant ceramic composite for use in advanced constructed facilities. The general work plan for this project is shown in Fig.1. Instead of selecting composite systems by trial and error, our work aims at developing a systematic approach for the design and optimization of ceramic composite properties for various applications in construction. A micro-mechanical model which can predict composite macro-behaviour from micro-properties such as fiber and matrix properties, fiber length and volume fraction, fiber/matrix interfacial properties as well as the residual thermal stresses in the composite (resulting from the different thermal expansion coefficients of fiber and matrix) will be developed through a coupled theoretical/experimental approach. This model, together with the understanding of techniques by which the micro-properties can be modified, will then allow us to design optimal composites. The development of the model will require an extensive research program and a model material which can be easily processed in the laboratory to provide test specimens will be used initially. After the micro-mechanical model has been developed and verified with the model composite, practical composite systems with optimized properties will then be designed for various applications. Such composites would then be tested under simulated service conditions to verify their actual performance.

During the previous one year of this project, short-fiber reinforced ceramic composite have been identified to be the class of ceramic materials with the highest potential to be developed into a construction material. A model composite system has also been chosen. In this project year, work has been concentrated on the processing and preliminary testing of model composites as well as the theoretical prediction of pre-peak behaviour of short-fiber composites. Also, a study on the potential of ceramics construction as well as obstacles to its use have been carried out to provide a foundation for our future work. Details of these works will be given in the sections below.

Statement of Problem Studied

(1) Assessment of the potential of ceramics to replace traditional construction materials by comparing the cost-performances of ceramics and concrete and investigating the promises for cost reduction of ceramics when applied to construction.

(2) Design of experimental set-up and development of a processing procedure for the fabrication of model composite specimens.

(3) Micro-mechanical modelling of the pre-peak tensile behaviour of short fiber reinforced ceramics, with special attention to factors affecting reliability and failure mode (single crack or multiple cracks) of the composite.

(4) Preliminary flexural test on specimens of the model matrix material as well as model composites with brittle and ductile fibers to identify micro-mechanisms in different material systems to provide insight for future modelling work.

Summary of Major Research Findings

(1) Potential of Ceramics as a Future Advanced Construction Material. To compare cost-performance of ceramics and concrete, a technique first suggested by Ashby[1] was applied to evaluate the cost-performance of materials. In this approach, cost and performance are considered together by looking at the cost of material required for a particular purpose. The cost-effectiveness of a material can then be expressed in terms of a parameter consisting of material cost, density and performance (which may be strength, modulus, material life, etc). In Table 1, for various applications, the cost-effectiveness parameter to be considered, the ceramic material to be compared, as well as the ceramic/concrete cost ratio are given. For ceramics to be a more cost-effective alternative to concrete, the ceramics/concrete cost ratio should be below unity. From the table, it can be noticed that the initial applications of ceramics in construction have to be chosen with great care. For normal structures where traditional materials such as concrete can satisfy performance requirement (e.g. normal residential buildings), the use of ceramics as a substitute may not be sound. However, in cases where traditional material cannot perform well (e.g. chemical tank, pavement for vertical take-off/landing aircraft) or where frequent repairs or replacement are anticipated (e.g. pavements), ceramics may be used as an alternative that is more economical in the long run.

While it is shown in Table 1 that for some applications, the use of ceramics may be economically sound in the long run, the initial material cost for using ceramics is at the present orders of magnitude higher than that of using concrete. However, when ceramics is applied to construction, its cost is expected to be reduced. Investigations have been carried out to look at the promises for cost-reduction of ceramics and the major reasons for one to expect decreasing ceramics costs are as follows:-

(i) *Cost trend due to mass production*

Ceramics, if used in construction, will be produced in large volumes. Mass production can lead to a lower cost as fixed overheads are shared over a larger volume of product. An example of decreasing cost trend is shown in Fig.2 for armour ceramics.[2]

(ii) *Simple shape and high tolerance for construction parts*

One major reason for current ceramics product to be expensive is the requirement of high tolerance. From Fig.3[3], it can be seen that the cost for finishing can be up to almost half the cost of the final product. In construction, a close tolerance is not required, and this will lead to a reduction of cost (Fig.4).[3] Also, the complicated shape of most ceramic products make powder compaction difficult and thus lead to a low yield of reliable parts. The simple shape of construction parts may enable a much higher yield and thus a much lower cost as reflected from the relation between cost and yield as shown in Fig.5.[4]

(iii) *Indirect savings due to the use of ceramics*

The high stiffness/weight and strength/weight ratios of ceramics allow longer span between supports. For example, less piers is required for a bridge, thus leading to significant saving. Also, by replacing concrete with ceramics, the weight of structural parts as well as the total weight of material to be handled are also reduced. This implies reduced cost in material cost transportation and less demand in the use of powerful equipment.

(iv) *Advances in ceramics technology*

Researches in ceramics have made available various low temperature processing techniques[5] and toughening techniques for the material.[6] Thus, it can be foreseen that with further research, ceramics with higher performance can be produced at lower costs.

As a conclusion of this study, it is suggested that for certain applications, ceramics is indeed a more economical alternative to concrete in the long run. However, the high initial cost of ceramics still make it hard to justify its use. Continued research on processing and toughening techniques to produce more cost-effective ceramics as well as reliable cost models to convince the material user that the promises for ceramic cost reduction mentioned above can indeed be realized are expected to gradually bring about the widespread use of ceramics in the construction industry.

(2) Experimental Set-up and Processing Procedure. In the first year of this project, a lead phosphate glass with various oxide additions has been chosen as the model matrix material. Graphite was chosen initially to be the fiber used in the model composite. However, the difficulty of fiber dispersion for high volume fractions (above 10%) and the excessive fiber breakage during mixing for low volume fractions lead to distributions of bundle sizes and fiber lengths which are not easy to determine. Hence, graphite fiber systems is not a good choice as an initial model composite system. It was decided that boron fiber and stainless steel fiber should instead be used for the processing of both brittle fiber composite and ductile fiber composite. Micro-mechanical models for both kinds of composite will then be developed.

The steps for composite processing have been determined through experimentation and are summarized in Fig.6. Following the procedure described in reference [7], the glass was fused at 400°C and refined at 700°C (for removal of water trapped in the lattice). One discovery we made which is not mentioned in [2] is that the temperature has to be raised slowly from 400°C to 550°C before a faster increase to 700°C to control frothing and prevent overflowing of glass. Since lead and phosphorus are both volatile materials, loss of such components during glass making have to be checked. Variable loss from batch to batch will lead to significantly different glass properties. X-ray fluorescence techniques have been employed to study the chemical composition of the initial powder mixture as well as the final glass to assess any loss of volatile components. This analysis has been carried out on two different batches and in both cases, loss of volatile components is not detectable. Thus, it can be concluded that no significant loss of volatile component results from our glass making process and glass property should be consistent from batch to batch.

After the glass is made, it is broken up into small pieces and milled with alumina balls for at least 10 hours. Fibers were then dry mixed into the glass powder. For rigid fibers such as boron and steel, adding fiber to glass powder in a bottle followed by shaking will result in good fiber dispersion. The mixture of glass matrix and fiber will then be hot-pressed in a die. After several trials, the best set-up for composite pressing was determined. This set-up is shown schematically in Fig.7. Mixture of matrix powder and fiber is put between two graphite punches in a graphite die. The inner wall of the die as well as the inner surfaces of the punches are lined with graphite foils to prevent wetting of graphite by hot glass which will then result in sticking and difficult specimen removal. To reduce porosity in the final composite, pressing is carried out in a vacuum. O-rings are thus used to seal the content of the die from the outside. Groves were cut on top of the lower punch and holes drilled to allow air to be pumped out from the inside of the die with a vacuum pump. To prevent heat loss to the surrounding, the whole assemblage is insulated at the sides. Before pressure is applied, the die is raised to a temperature of 300°C and left there for about 15 minutes for its content to reach the same temperature. A pressure of 500-600 psi was then applied for 5 minutes. The temperature was then raised to 350-400°C (with pressure still acting). It takes about 10-20 minutes to reach this higher temperature. Pressure is applied for a further 15 minutes. The specimen is then ejected hot, cooled down and cut into beam specimens to be subsequently tested.

(3) Micro-mechanical Modelling of Pre-peak Tensile Behavior. Short-fiber composites have the advantage of easy processing in comparison with continuous fiber composites. However, relative few investigations on their mechanical performance have been carried out compared with continuous fiber composites. In this year, our theoretical investigations have been concentrated on the micromechanical modelling of pre-peak tensile behaviour of short fiber reinforced composites. In Ref.[8,9], continuous fiber composites have been shown to possess high material reliability and a kind of pseudo-ductility accompanied by multiple matrix cracking which gives warning before final failure occurs. Intuitively, one would expect that discontinuous fiber composites may possess the same kind of desirable behaviour depending on how long the discontinuous fibers are and one may then be able to have fibers short enough for convenient processing but still long enough to give high material reliability and multiple cracking. One focus of our work, therefore, is to determine the criteria to design short-fiber composites that have similar behaviour to continuous fiber composites.

The reliability of composites are usually accessed by considering the variation of first-cracking strength with inherent flaw size. The first-cracking strength is defined as the applied stress at which a crack is formed across a complete section of the material. It may or may not be equal to the ultimate strength of the composite, depending on whether the fibers that are still bridging the crack can take further load. In our work, a fracture mechanics approach was employed to study the first-cracking behaviour of short-fiber reinforced brittle matrix composites. Results are described in detail in Appendix 1. In the following, important findings and their implications to composite design will be highlighted.

From our analysis, it is discovered that material properties affecting behaviour of short-fiber reinforced composites (sfrc) including matrix and fiber elastic properties, matrix toughness, fiber length, radius and volume fraction, interfacial strength can be grouped into a single dimensionless term (L/u_c) that governs the behaviour of sfrc. From Fig.8 (which is the same as Fig. A2 in the Appendix), sfrc with small values of L/u_c behave similarly to continuous fiber composites while sfrc with large L/u_c behave similarly to brittle Griffith materials. For small L/u_c values, the large range of flaw size over which the stress remains constant implies insensitivity of strength to flaw size and thus high reliability. (Note that in most practical cases, the size of the largest flaw in the composite is close to or within the range of flaw size where stress remains constant) Moreover, since stress remains constant with increasing flaw size, the load carrying capacity will not decrease with crack growth and is the same before and after first-cracking, though after first-cracking, the load is taken by the fibers alone. If the fibers can take further load, the ultimate strength will be substantially higher than the first-cracking strength and multiple cracking can occur as the applied stress is increased beyond the first-cracking strength. Thus, for small values of L/u_c, short-fiber composites will also have the desirable features of high reliability and multiple cracking.

L/u_c is therefore an important parameter to be considered in the design of short fiber composites. From the theoretical analysis, L/u_c is proportional to $[\, K_c^2\, r^2 /(V_f\, \tau^2\, l^3)]^{2/3}$. For a certain composite system, K_c, the composite toughness is fixed. If l is fixed (at, for example, the maximum length for convenient composite processing), L/u_c can be reduced by increasing the fiber volume fraction V_f, decreasing the fiber radius r (which can be easily done by drawing for metallic fibers by drawing) or increasing the interfacial shear strength τ

(through fiber surface treatment). The value of L/u_c has been computed for several practical short-fiber composite systems such as carbon fiber/pyrex glass, glass fiber/epoxy, steel fiber/concrete and silicon carbide whisker /silicon nitride. For all these composite systems, for a value of l/r about 100, if more than 10% of fiber is used, the value of L/u_c is low enough for composite behaviour to approach that of continuous fibers. This shows that a relatively low volume percent of short fibers is enough to give high material reliability. From this theoretical study, a criteria for the design of short fiber composites have been established. In this study, the effects of fiber inclination and residual thermal stresses on composite behaviour have not yet been considered. The incorporation of such effects into our theoretical model will be topics for research in the next project year.

(4) Experimental Studies of Model Composite. Specimens of the model glass as well as model composite systems with stainless steel fibers and boron fibers have been processed according to the procedure described in (2). Such specimens have been tested in flexure to study their behaviour qualitatively to provide insight for further modelling work. The load-displacement curves for the glass itself, glass reinforced by 1% of boron fiber and glass reinforced by 1% of steel fiber are summarized in Fig.9. For the glass, there is no post-peak strength. The addition of fiber, even at a low volume fraction of 1%, gives rise to significant post-peak strength due to fiber bridging effect. When boron fiber, a brittle fiber, is used as reinforcement, the post-peak behaviour shows a zig-zag form. On the other hand, if a ductile fiber such as steel fiber is used, there is a long tail in the post-peak part. Micrographs of the failure surface for both composites are taken with a Scanning Electron Microscope (SEM) and is shown in Fig.10 and 11. It can be seen that boron fibers tend to break at a point close to the matrix surface (Fig.10) while steel fibers tend to be pulled out (Fig.11). Post-peak softening

behaviour due to fiber pull-out is well documented. However, even for fibers that will ultimately break, such as in the boron fiber composite system, it was found that significant post-peak load capacity can still be attained. In such composites, after the peak load is reached, a crack is formed but the fibers can still bridge the crack and support some load. Further deformation will open up the crack leading to breakage of fibers one after the other. Successive fiber breakage is also evident from the fact that cracking sound can be heard during the experimental when the boron fiber composite specimen is loaded beyond its peak strength.

In both of the composites, the fibers are randomly distributed and the breakage of fiber is thought to be mainly due to the bending of fibers inclined to the plane of the crack. (In one of the boron fiber composite specimens, a fiber happens to lie almost perpendicular to the crack plane and was completely pulled out.) For brittle fibers, more breakage occurs while inclined ductile fibers can allow more deformation under bending and there is a higher chance for fiber pull-out to take place. These experimental observations suggest that investigation of the load capacity of inclined fibers as well as the effect of fiber inclination on breakage and pull-out of fibers are important for prediction of the post-peak behaviour of composites. These tasks will be carried out in the next project year.

Participating Scientific Personnel

1. Victor C. Li, Associate Professor of Civil Engineering, MIT. Principle Investigator on this project.

2. Christopher K.Y. Leung, Ph.D candidate, Dept. of Civil Engineering, MIT. Graduate research assistant on this project.

3. John Haggerty, Senior Research Scientist, Dept. of Material Science and Engineering, MIT. Consultant on this project.

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1. Li, Victor C & Leung, Christopher K Y "Ceramics for Construction" Construction & Building Material Vol 2, No 2 June 1988.

2. Leung, Christopher K & Li, Victor C "First-Cracking Strength of Short Fiber Reinforced Ceramics" accepted for presentation at the 13th Annual Conference on Composites and Advanced Ceramics, Cocoa Beach, Fl, Jan 15-18, 1989.

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Appendix 1:-
Reliability of First-Cracking Strength for Short-fiber Reinforced Brittle Matrix Composites

A brittle material is also a material with low reliability, i.e., its strength is very sensitive to the size of flaws in the material. Such flaws may be formed during processing, machining or handling and are very hard to control. The introduction of fibers into a brittle material can greatly reduce the variability of its strength with flaw size and hence improve its reliability. By determining the first-cracking strength vs flaw size relation for continuous fiber composites, Marshall et al [A1,A2] showed explicitly the theoretical improvement of reliability by adding continuous fibers. In this paper, a similar approach is employed to study the reliability of short-fiber reinforced brittle matrix composites. Comparison with continuous fiber composites and brittle materials will be made and important parameters affecting the reliability of short fiber composites will be discussed.

The first-cracking strength is the applied tensile stress at which an inherent flaw will propagate unstably across the whole section of the material. Its relation with flaw size can be obtained by a fracture mechanics approach. In this study, the flaw is assumed to be a penny-shaped crack in an infinitely large body under uniform tension. The first-cracking strength s is then the applied tension at which the sum of stress intensities at the crack tip due to s and the bridging force in the fibers (which are of opposite signs) equals a critical value K_c. To avoid tedious computation, two simplifying assumptions are made. The crack profile is assumed to be the same as one with uniform loading acting on the crack. The relation between stress in bridging fiber and crack opening is obtained by assuming a uniform shear stress along the debonded part of the fiber (hence a square root relation between stress and crack opening) and a linear drop of load with crack opening as the fiber is pulled out (Fig.A1). Moreover, no distinction is made between aligned and random fiber composites.

The present analysis shows that σ, when normalized by σ_m, can be expressed in terms of three other dimensionless terms c/c_m, u_c/l and
L/u_c, where

c = size of the flaw

l = maximum embedded length of the fiber = fiber length/2

$$\sigma_m = [1.5\ \pi^{1/2} K_c^2 \alpha^2\ \beta]^{1/3}$$

$$c_m = [9K_c\pi/4\alpha^2\beta]^{2/3}$$

$$L = [1.5\pi^{1/2} K_c^2 \beta/\alpha]^{2/3}$$

$$u_c = \tau l^2/E_f R(1+V_f E_f/V_m E_m)$$

$$\alpha = [4V_f^2 \tau E_f(1+V_f E_f/V_m E_m)/R]^{1/2}$$

$$\beta = 2(1-\upsilon^2)/(E_c \pi^{1/2})$$

τ = interfacial friction between fiber and matrix

R = radius of fiber

V_f, V_m = volume fractions of fiber and matrix respectively

E_f, E_m = Young's modulus of fiber and matrix respectively

E_c , υ = Young's modulus and Poisson's ratio of the composite

$K_c = (E_c/E_m)\ K_m$, where K_m is the matrix fracture toughness

For most practical composite material systems, L/u_c range from 0.01 to 3 and u_c/l lies within 0.0005 and 0.02. The normalized stress vs normalized flaw size curves for various values of L/u_c and $u_c/l = .005$ are plotted in Fig. A2. From the figure, it is obvious that the behaviour of short-fiber composites is significantly affected by the parameter L/u_c. For small values of L/u_c, the behaviour approaches that of continuous fiber composites. The strength reaches a constant value after a certain flaw size. If the inherent flaw size of the material happens to lie close to or within these constant stress range, the reliability of the material will be very high. Indeed, this is usually the case because factors that tends to decrease L/u_c, such as high fiber volume fraction, small fiber diameter, low matrix toughness and high interfacial shear friction will also decrease c_m. Once the size of c_m approach the microstructural size of the composite (such as fiber size or fiber spacing), it is very likely that the maximum inherent flaw size is close to or larger than c_m and hence the material will have a very high reliability.

For composites with small L/u_c, the constant value of stress for flaw size above a certain value implies that crack size can increase under constant stress until a crack is formed across the whole section of the material. In this case, the load carrying capacity before and after first cracking is the same, although after cracking, only the fibers are taking the load. If the fibers are strong enough to take further load, the ultimate strength can be substantially higher than the first cracking strength and multiple cracking will occur when the applied stress is increased beyond the first cracking strength.

For larger L/u_c, during crack growth, the applied stress will decrease. The first-cracking strength is thus the ultimate strength. Composite behaviour will be similar to that of a Griffith material though the curve lies much higher than the Griffith curve and is dropping less steeply, still showing improved reliability, especially in the range of c/c_m less than unity. In most real material systems with large L/u_c, c_m is of the order of 100mm and c/c_m is clearly less than unity.

There is a certain critical L/u_c value which marks the transition between these two kinds of behaviour. This critical number is 1.45 in the present case. For $l/r=100$, some real material systems with $L/u_c < 1.45$ are SiC Whisker/Si_3N_4 (V_f=10-25%), graphite/ Borosilicate Glass (V_f=10-30%) and Glass/Epoxy (V_f=15-40%). A material system with $L/u_c > 1.45$ is 1% steel fiber reinforced concrete. (Note:- with V_f greater than about 4%, steel fiber reinforces concrete will have a value of $L/u_c < 1.45$.)

The variation of the strength vs flaw size relation with u_c/l for $L/u_c = 3$ is illustrated in Fig. A3. Note that for practical values of u_c/l, the composite behaviour is not sensitive to this parameter. Actually, for small L/u_c values, the variation with u_c/l is so small that the curves if plotted together, will be almost indistinguishable.

While the increase in fiber length can lead to an advantageous decrease of L/u_c. However, an excessively long fiber length should not be used. Too long a fiber would make processing difficult. Moreover, after first cracking, if the load is further increased, a long fiber will break while a short one tends to be pulled out. The pull-out of fibers absorbs more energy and also give the composite more pseudo-ductility. For structural component which is not under uniform load, this will prevent the extension of damage to other parts of the component.

It should be pointed out that the above analysis does not take into account the possibility of fiber breakage before first cracking. This can be easily checked by computing the maximum crack opening for each crack size and then deduced the bridging stress in the most highly stressed fiber. If this stress is below the fiber strength, fiber breakage will occur. In composite design, this check is important as early breakage of fiber will lead to a low toughness, low reliability material and so should be avoided.

From this study, it can be concluded that L/u_c is an important parameter governing the reliability of short fiber composites and should be a useful parameter for the design of such composites.

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TABLE 1 :- CERAMIC/CONCRETE COST-PERFORMANCE COMPARISON

Applications	Structural Failure Mode	Parameter to be Considered	Ceramic for Comparison	Ceramic/Concrete Cost Ratio
Beam/Slab	Flexural Failure of Plate	$C\rho/(\sigma_f)^{0.5}$	Alumina	123
Beam/Slab	Excess Deflection of Plate	$C\rho/(E)^{0.5}$	Alumina	289
Short Column	Crushing	$C\rho/\sigma_c$	Alumina	14
Long Column	Buckling	$C\rho/(E)^{1/3}$	Alumina	408
Rigid Pavement	Plate Bending on Elastic Foundation	$C\rho/(\sigma_f)^{0.5}$	Alumina	123
Pavement Surface	Excessive Wear	$C\rho/\sigma_c$	Alumina	14
Pavement Under Stress	Subcritical Crack Growth	$(C\rho)$/ (Pavement Life)	Alumina	<< 1
Pavement for Vertical Takeoff/ Landing Aircraft	Thermal Spalling	$C\rho$/(No. of Thermal Impact to Failure)	Ratio may be < 1 for some ceramics (refer to text for details)	
Chemical Tanks	Chemical Corrosion	$(C\rho)$/(Tank Life Under Corrosion)	Silicon Carbide	<< 1

Notes :- (1) In the Table, the cost and properties of alumina are taken from Ref. 24 for Liquid Phase Sintered Alumina and are listed as follows:-
Cost (C) :- \$20 per kg (\$20,000 per tonne)
Relative Density (ρ) :- 3.55
Compressive Strength (σ_c) :- 3000 MPa
Flexural Strength (σ_f) :- 310 MPa

(2) Cost of Concrete is taken to be \$36 per tonne (from Ashby & Jones:- Engineering Materials 2, Pergamon Press, 1986). Relative Density of Concrete is 2.4. The mechanical properties of Concrete are tabulated in Table 1. In cases where a range of value is given, the middle value in the range is used.

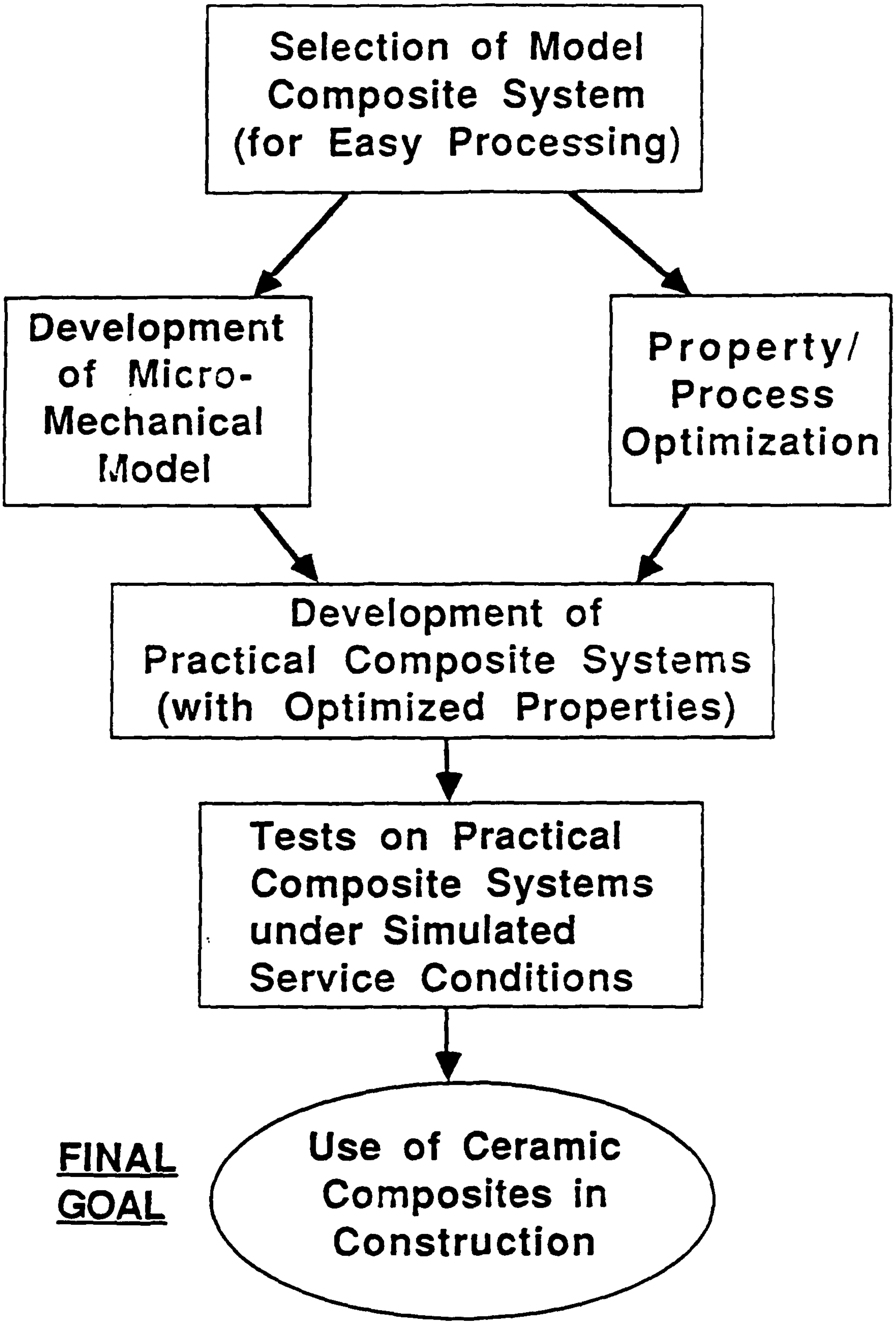


Fig. 1 Major Tasks of a Five-Year Research Work Plan

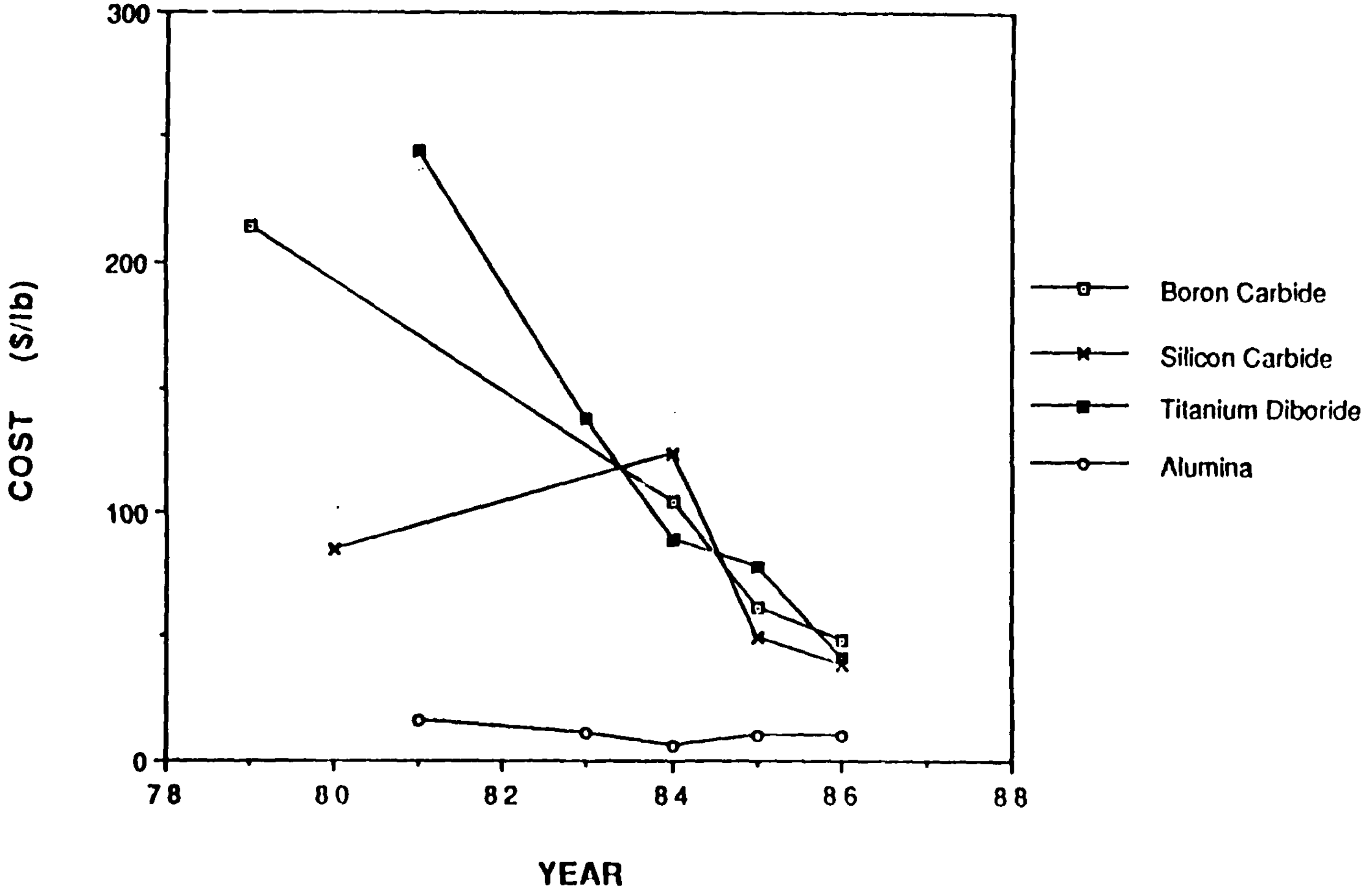


Fig.2 Cost Trend of Some Armour Ceramics

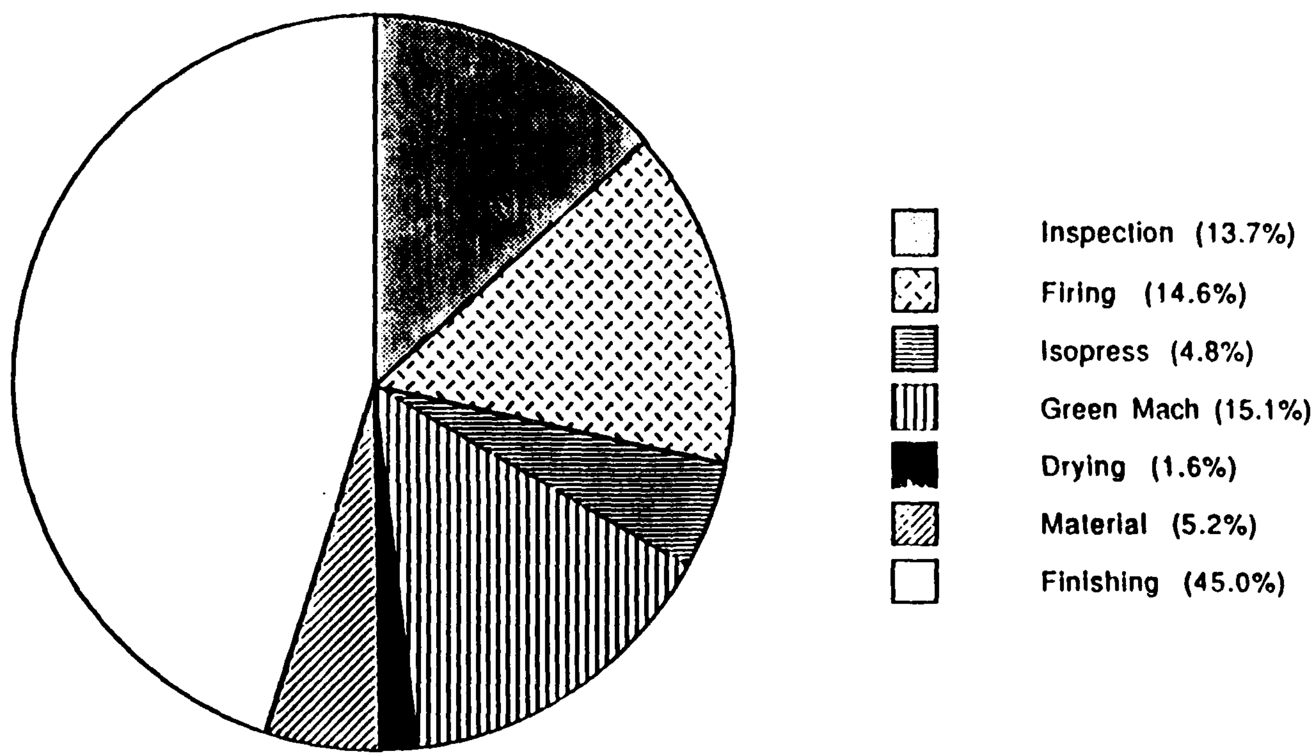


Fig.3 Cost Distribution of SiC seals 5cm in diameter, assuming a $2.90/kg powder and 40% yield

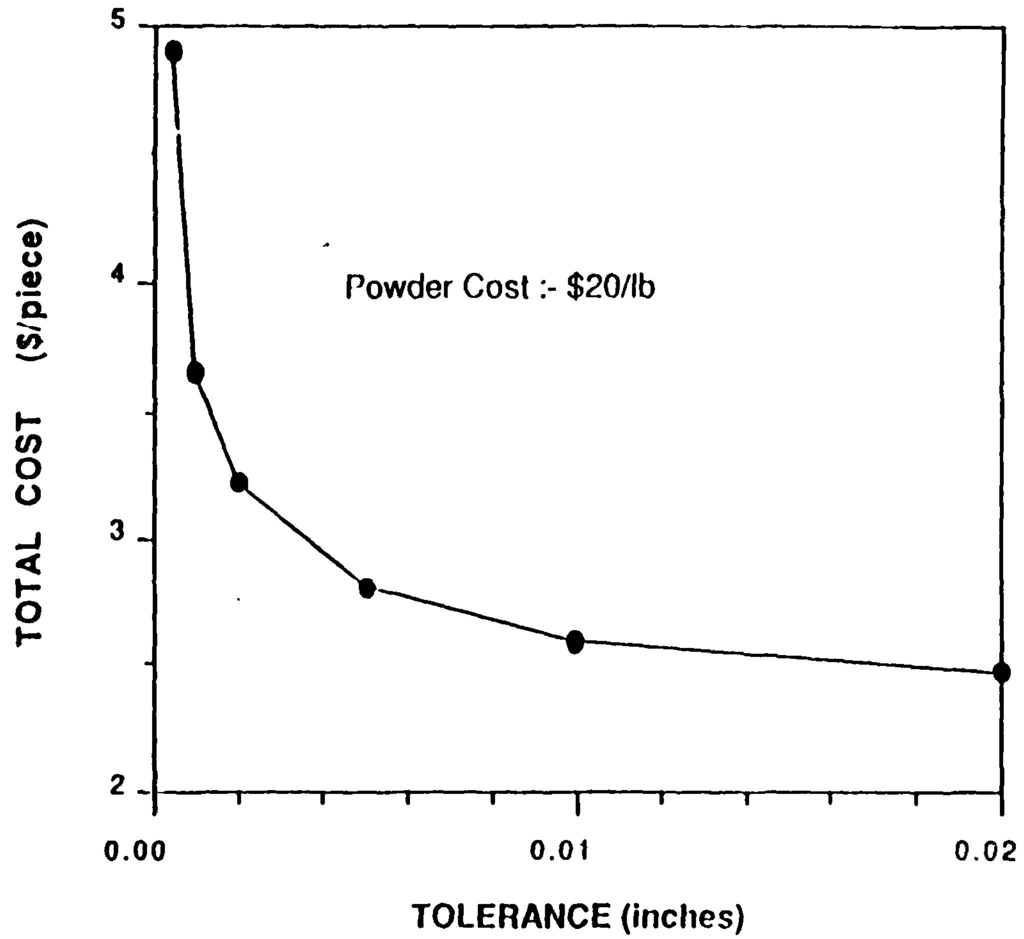


Fig.4 Cutting Tool Insert Cost vs Tolerance

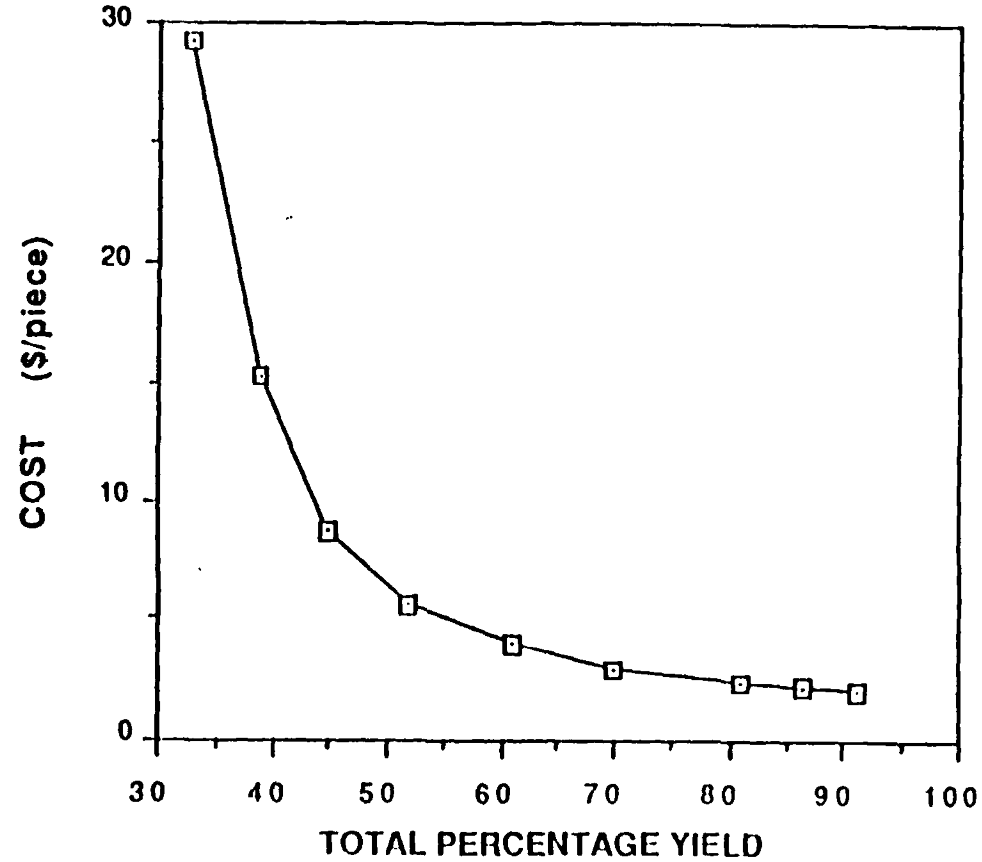


Fig.5 Silicon Nitride Cutting Tool Insert Cost vs Total Percentage Yield for HIP/Sintering

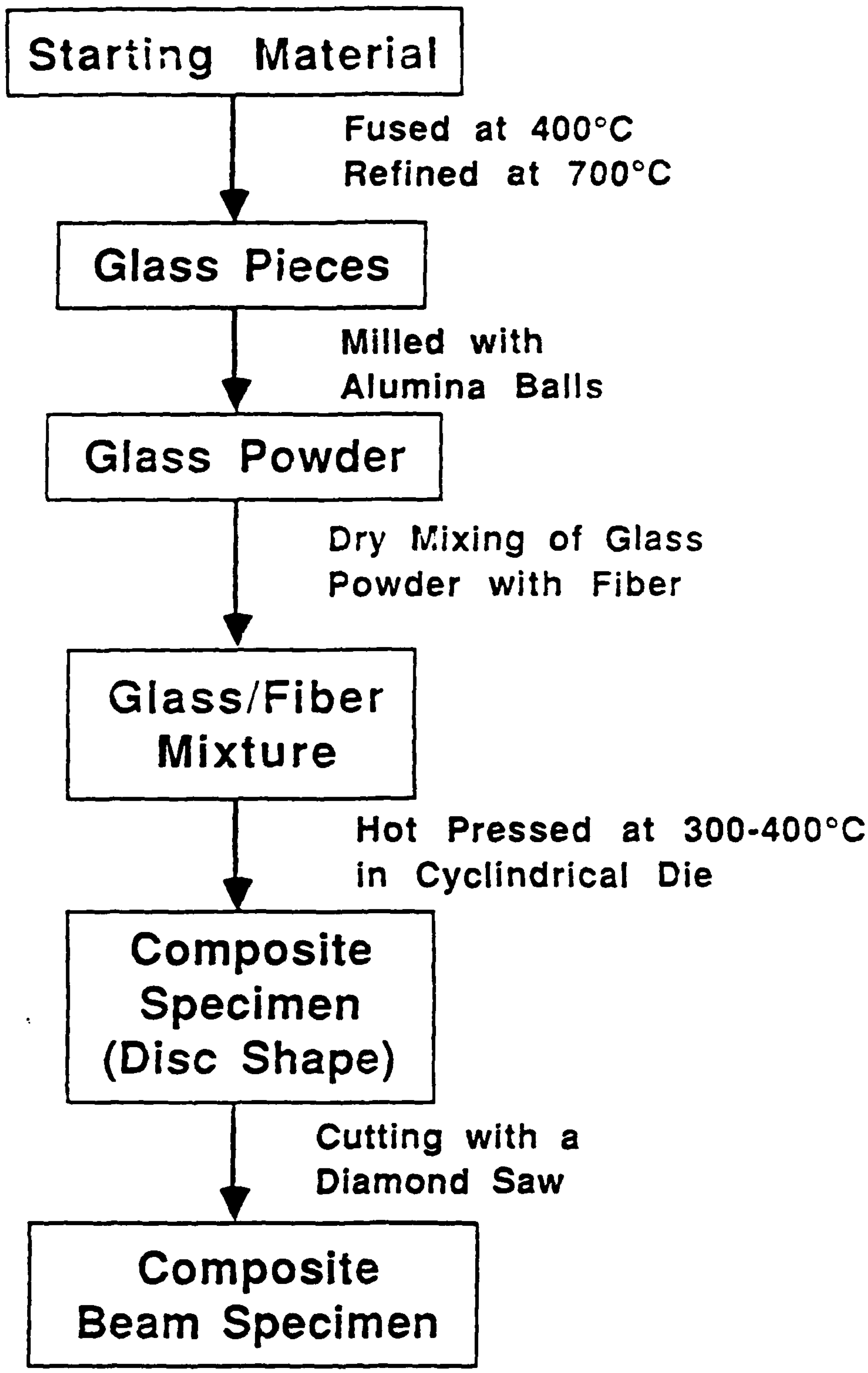
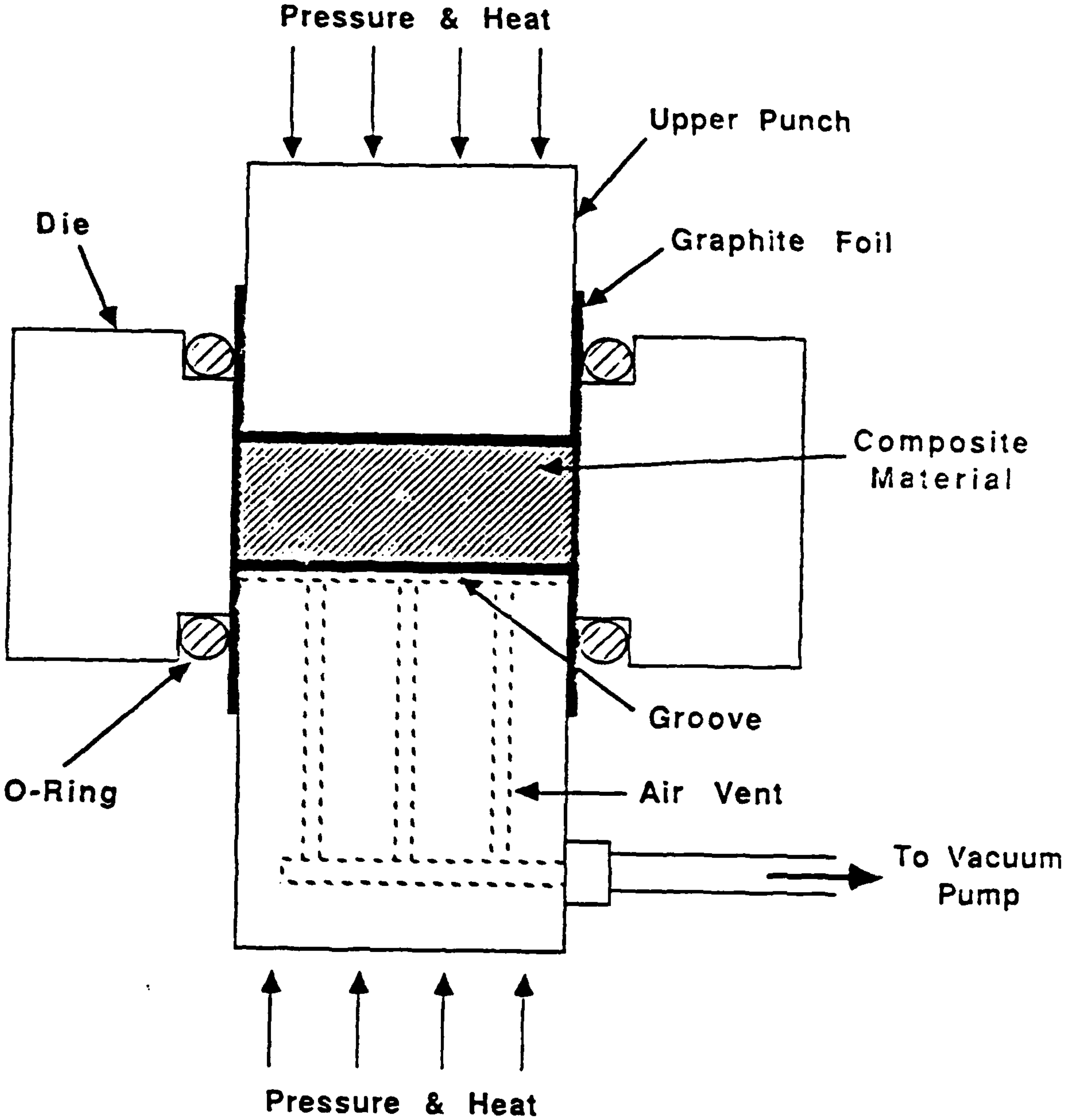


Fig. 6 Procedure for Preparation of Composite Specimen



Note: The whole set-up is insulated at the sides to prevent heat loss to the surrounding

Fig. 7 The Set-Up for Pressing of Composite Specimens

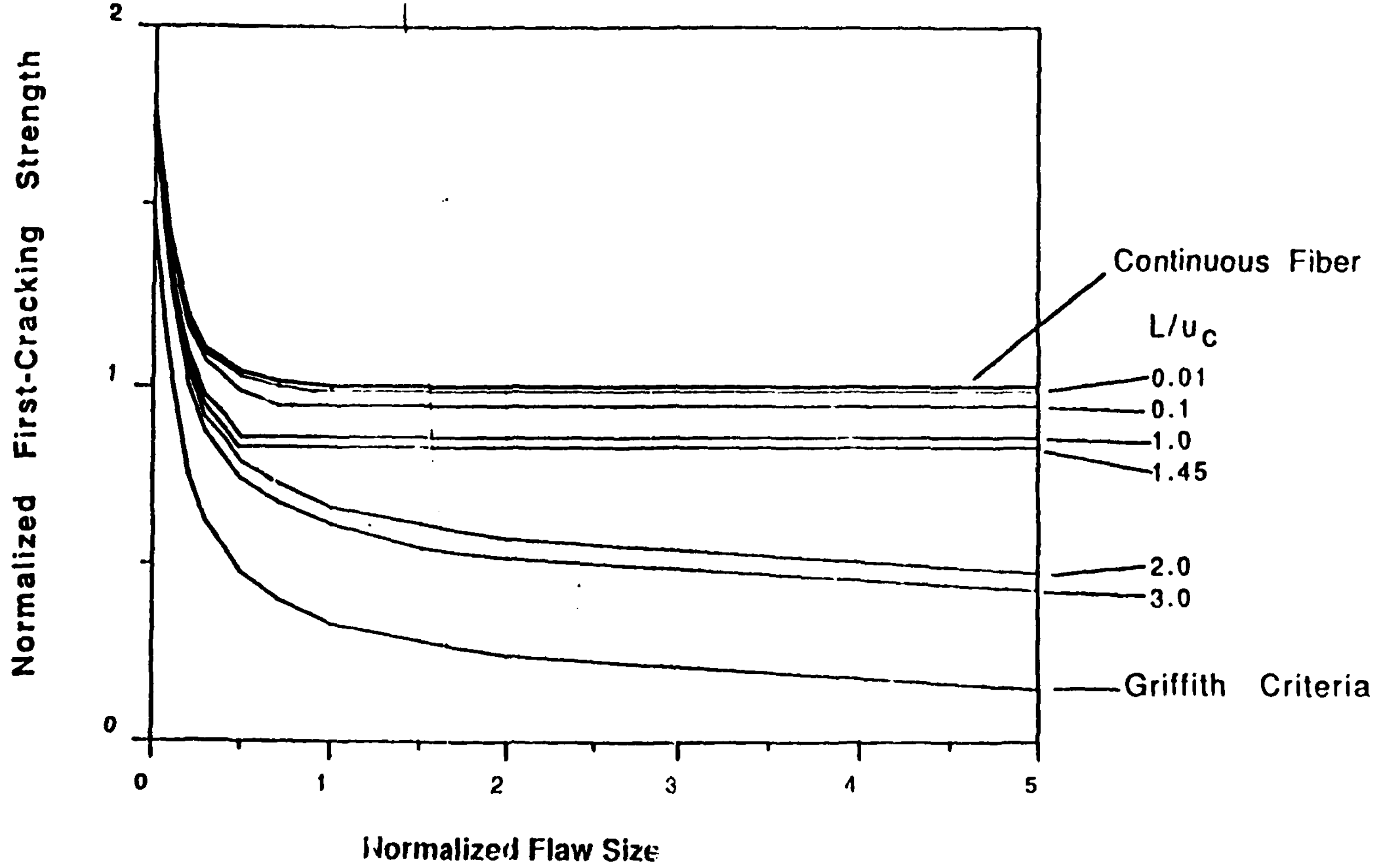


Fig. 8 Curves of Normalized First-Cracking Strength vs Normalized Flaw Size for various L/u_c with $u_c/l = 0.005$

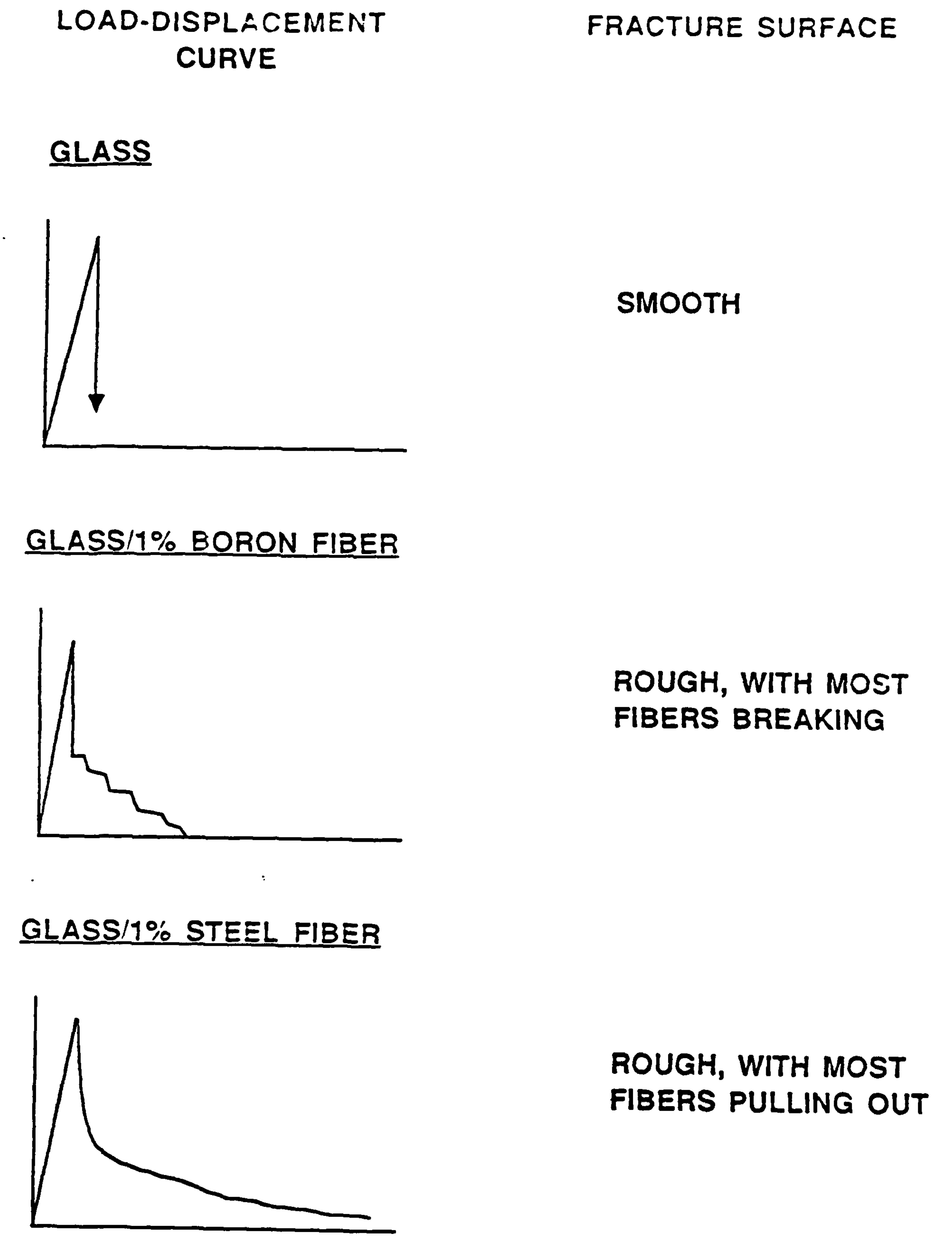


Fig.9 Load-Displacement Curves and Fracture Surface Apperances for Glass with and without Fiber Reinforcement

Boron Fibers

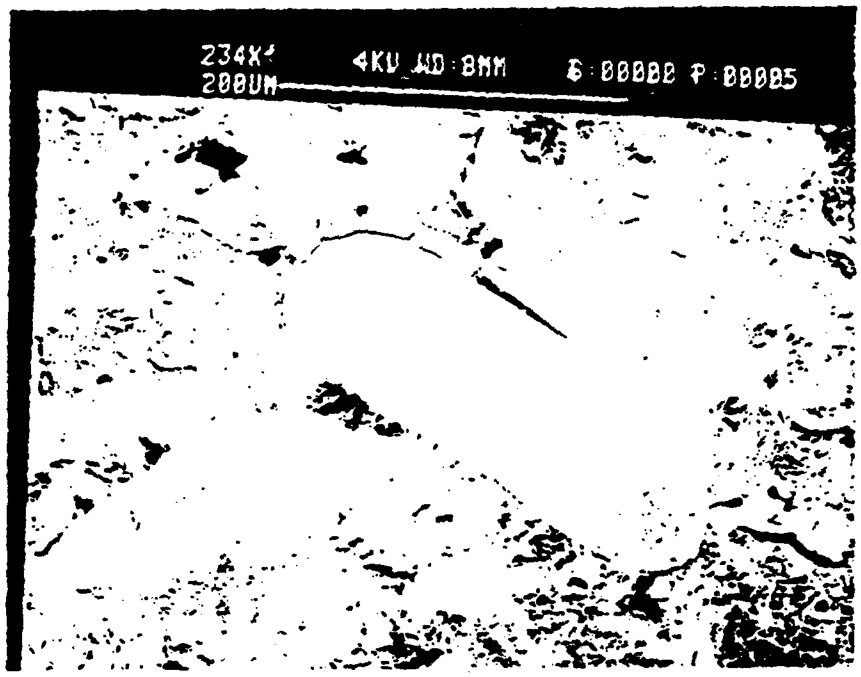


Fig.10 Breakage of Boron Fibers Near the Crack Face

Steel Fiber

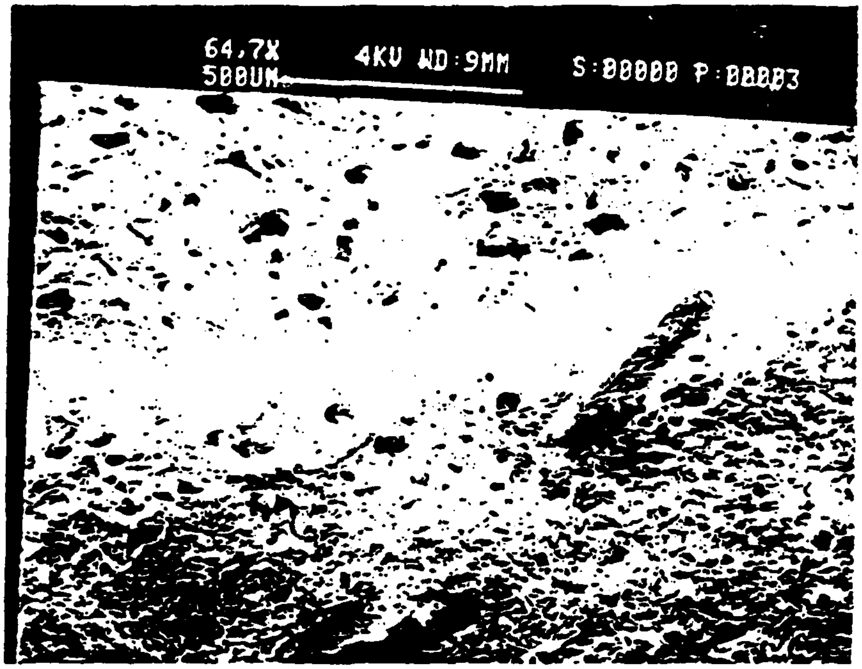


Fig.11 Pullout of Steel Fiber from the Matrix

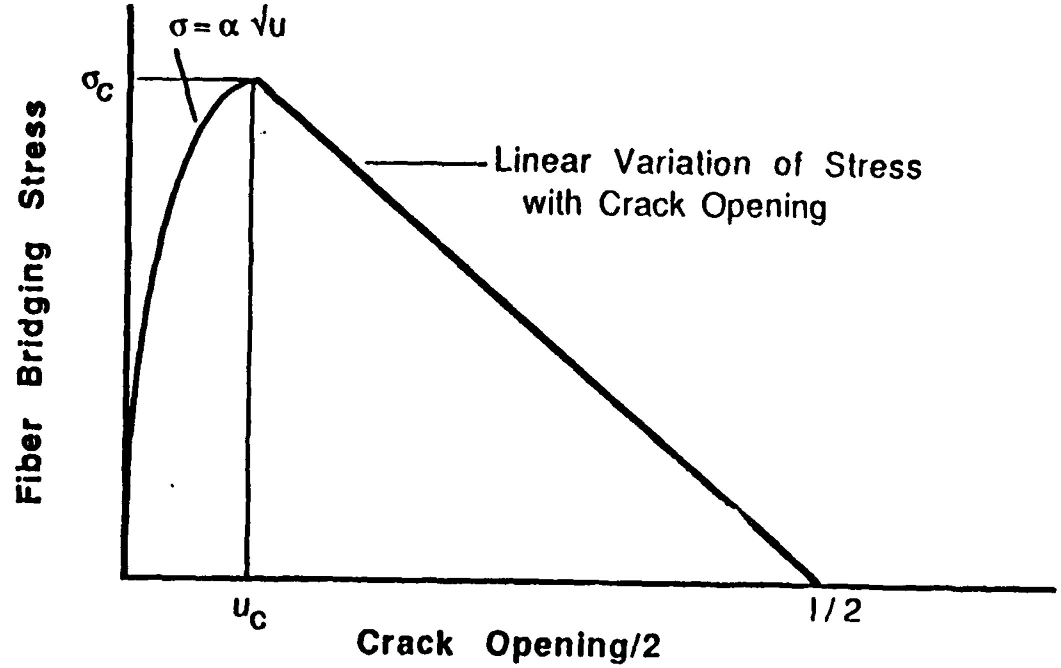


Fig. A1 Fiber Bridging Stress vs Crack Opening

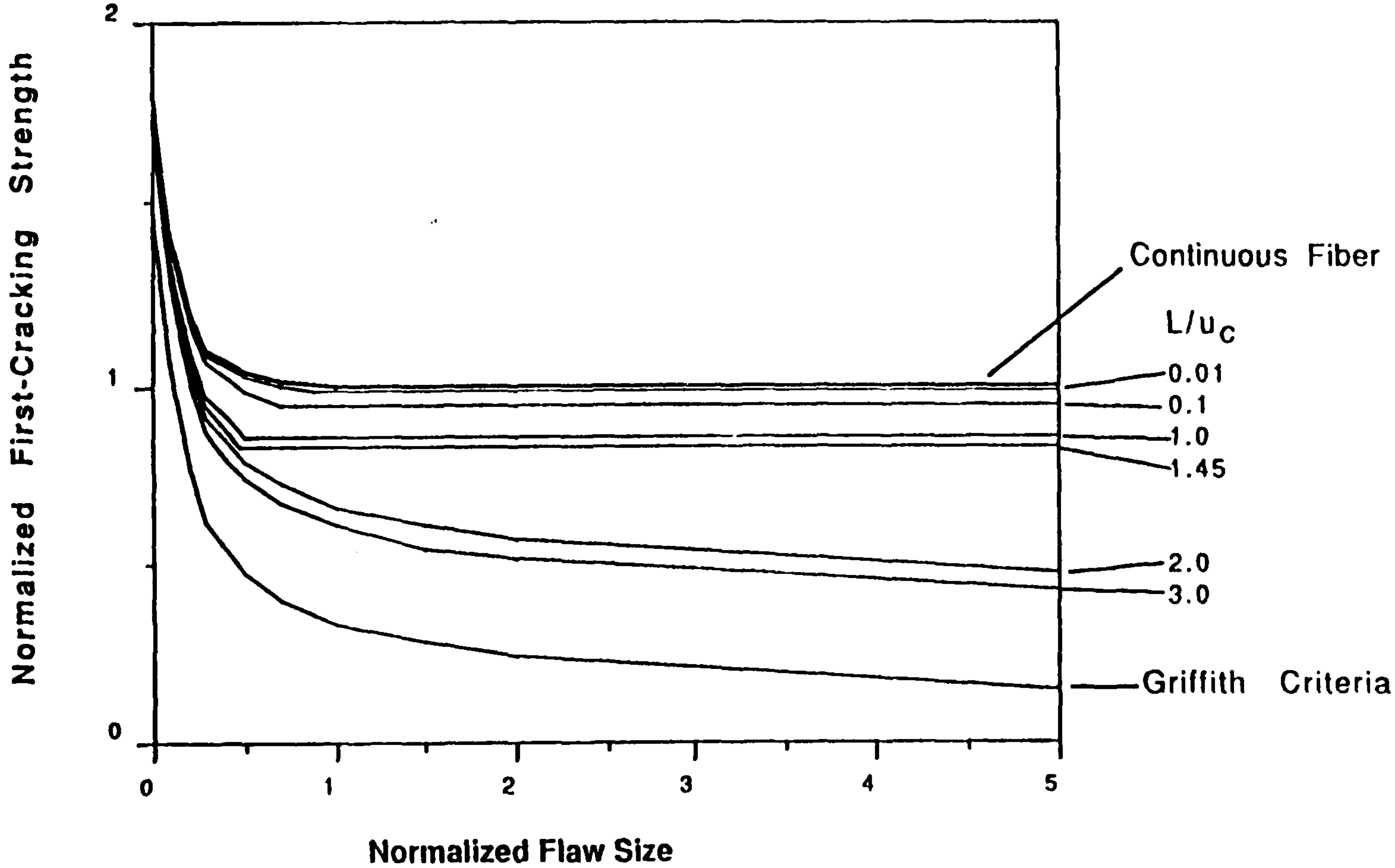


Fig. A2 Curves of Normalized First-Cracking Strength vs Normalized Flaw Size for various L/u_c with $u_c/l = 0.005$

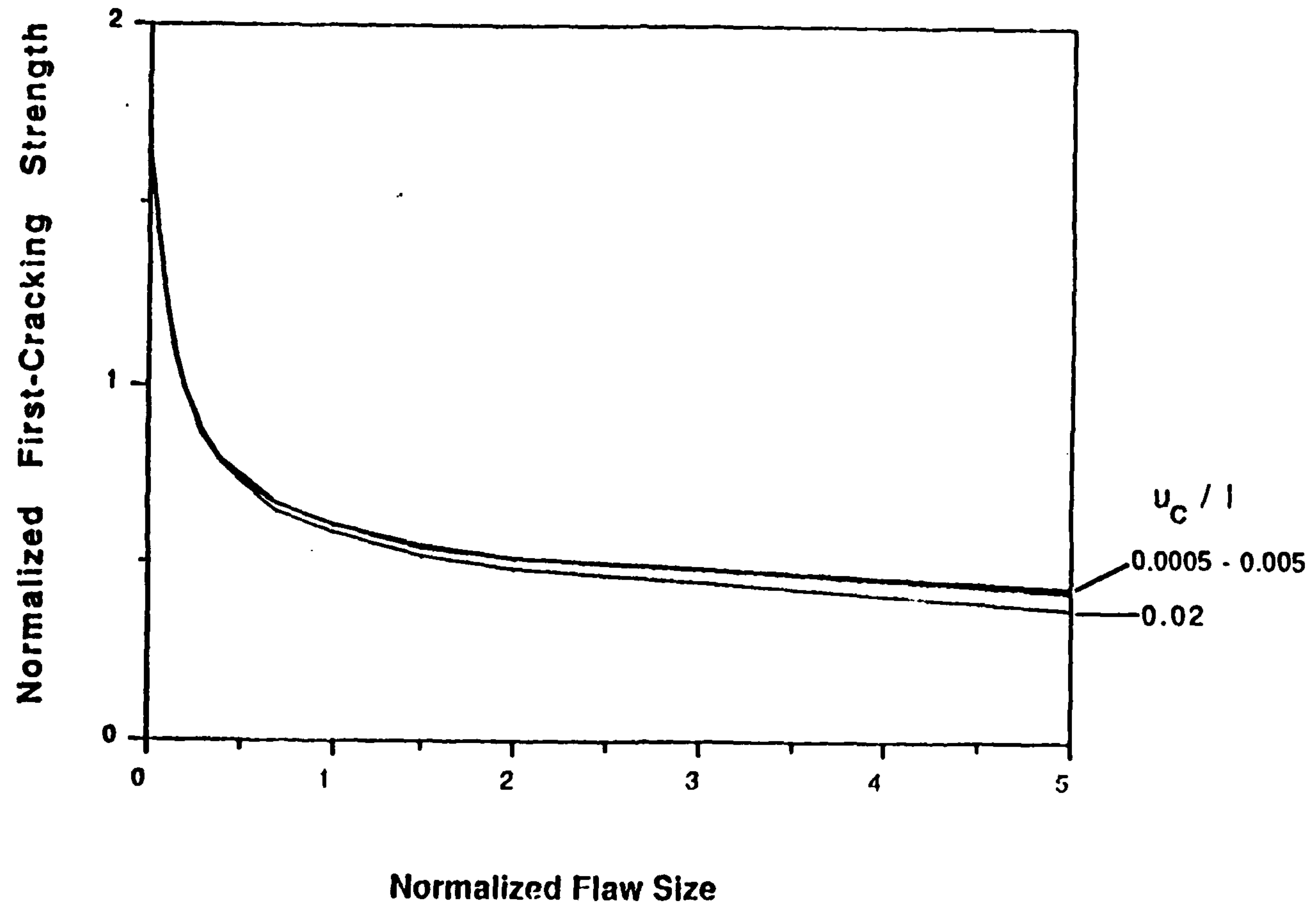


Fig. A3 Curves of Normalized First-Cracking Strength vs Normalized Flaw Size for various u_c /l with L/u_c = 3.0